# ASSESSING FIRE BEHAVIOR POTENTIAL: A COMPARATIVE ANALYSIS OF TWO SPATIAL TECHNIQUES

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## ABSTRACT

Sustainable forest management in fire dependent ecosystems requires an assessment of forest fire behavior potential at the landscape level. This study compares the results of two spatial and quantitative techniques for evaluating fire behavior potential in a 505,800 ha area located in southwestern Alberta. A compilation of 10 years of fire weather/danger data from multiple weather stations was used with fuels and topographic information to derive head fire intensity (HFI) values over the study area using the Canadian Forest Fire Behavior Prediction System and the Spatial Fire Management System. The first method (daily) requires the creation of an HFI map for each of the 595 days in the study period. Historical HFI frequencies are then calculated for every pixel allowing the desired percentile maps to be produced. The second method (climatological) computes the historical fire weather/danger frequencies for each weather station before spatial modeling and then creates one HFI map for every percentile analyzed. Either method can be used to identify areas of extreme fire behavior potential; this information can serve in numerous fire and forest management activities. The daily method provides the most representative assessment of fire behavior potential but it is computationally demanding. The climatological method is considerably faster and requires less computing power but tends to overestimate the fire behavior potential, especially at the higher percentile levels.

Keywords: Alberta, fire behavior potential, fire management planning, forest management planning, wildfire threat assessment

## INTRODUCTION

Sustainable forest management is a challenging endeavor that requires knowledge and understanding of past and projected natural disturbances. In Canada, recent severe fire seasons have shown that it is not economically possible to suppress all forest fires; neither is it ecologically desirable since forest fires are a primary natural agent of change in many of Canada's forest ecosystems. Therefore, steps must be taken to integrate fire into land and resource management to enhance environmental and economic sustainability. An essential aspect of this process is the spatial and quantitative assessment of forest fire behavior potential at the landscape level.

Advances in Geographic Information Systems (GIS) have led to the development of a number of spatial techniques for assessing wildfire threat (e.g., Chatto 1998, Hawkes et al. 1996, Sneeuwjagt 1998). One of the major components of these studies is the ability to evaluate fire behavior potential using a relative weighting scheme for selected fire behavior characteristics. As an alternative, Taylor et al. (1998) developed a quasi-spatial, quantitative assessment technique but it can only be applied to relatively small areas containing a single representative weather station. The purpose of this study is to compare 2 landscape-level methods (i.e. daily and climatological) that are both spatial and quantitative, for assessing forest fire behavior potential. This work was initiated as part of the Southern Rockies Landscape Planning Pilot Project which is aimed at developing spatial modeling tools to support new directions for the implementation of sustainable forest management in Alberta (Tymstra 1998).

## STUDY AREA

The 505,800 ha study area is located in southwestern Alberta on the eastern side of the continental divide (Figure 1). The area is part of the Main and Front Ranges of the Canadian Rocky Mountains. The elevation varies from 1050 m in the east to 3100 m in the west as the landscape changes from gently rolling grasslands to forested foothills and steep mountains. Recreational activities (camping, hiking, hunting, fishing, etc.), timber harvesting, livestock grazing, and oil and gas extraction are common in the area.

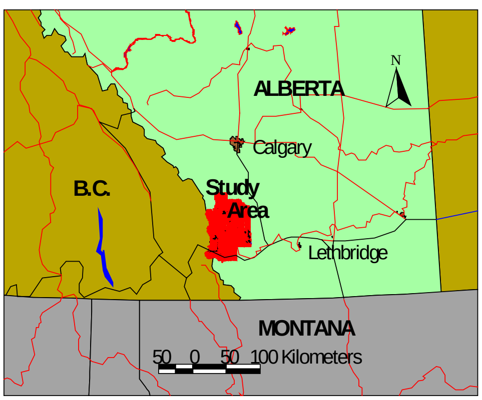


**Figure 1. Location of the study area in Alberta, Canada.**

The climate consists of cold winters (January mean: -9°C) with abundant snowfall and cool summers (July mean: 15°C) with considerable rainfall (Longley 1972, Forestry Canada and Alberta Forest Service 1992). The area is relatively windy and frequently subject to Chinook winds that cause periods of mild winter temperatures (Longley 1972).

The study area contains five of Alberta's natural sub-regions: alpine, subalpine, montane, aspen parkland, and fescue grass (Forestry Canada and Alberta Forest Service 1992). The alpine natural sub-region has only sparse vegetation. Dominant tree species in the subalpine sub-region include Engelmann Spruce (*Picea engelmannii* Parry ex Engelm.), White Spruce (*Picea glauca* (Moench) Voss), Subalpine Fir (*Abies lasiocarpa* (Hook.) Nutt.) and Subalpine Larch (*Larix lyallii* Parl.) (Rowe 1972). Montane vegetation is characterized by closed stands of Lodgepole Pine (*Pinus contorta* Dougl. ex Loud.) and open stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). Aspen (*Populus tremuloides* Michx.) stands and grasslands are found in the eastern and southern portions of the study area (Forestry Canada and Alberta Forest Service 1992).

The historic fire regime of the subalpine natural sub-region is one of infrequent, large, high intensity stand replacing crown fires (Tymstra 1998). The other sub-regions are characterized historically by more frequent, small to medium sized fires that exhibit low to moderate fire intensity. A majority (54%) of the stands in the study area originated between 1890 and 1929 (Tymstra 1998) and a significant reduction in area burned has been observed since the introduction of effective fire suppression in the 1940s.

Although wildfires can occur in the study area at any time of the year, they are most common in July and August. Between 1961 and 1996, 457 fires were reported, burning a total area of 3422 ha. Seventy-seven percent of these fires were person-caused and 23% were due to lightning (Tymstra 1998). Lightning frequency increases from the continental divide to the east and northeast but the majority of lightning-caused fires are observed in the Porcupine Hills in the eastern portion of the study area (Tymstra 1998). Person-caused fires occur mostly in the southern portion of the study area where towns, railways, highways, and recreation areas are most prevalent.

## METHODS

### Assessing Fire Behavior Potential

Fire intensity is defined as the rate of energy release per unit time per unit length of fire front (Byram 1959). It provides a comprehensive measure of fire behavior potential and it has been related to fire behavior characteristics (Table 1), fire effects and suppression effectiveness. Fires with head fire intensity (HFI) values between about 2000 and 10,000 kW/m are of special interest because they begin to exhibit crowning which makes them more difficult to control. Fires below 2000 kW/m can generally be contained by initial attack crews (Hirsch et al. 1998) whereas those over 10,000 kW/m are usually beyond the control of suppression resources.

The HFI values obtained in this study were calculated using the Canadian Forest Fire Weather Index (FWI)

| Head Fire Intensity class (kW/m) | General Fire Behavior Description |
|---|---|
| 0-9 | Smoldering or subsurface fires with little or no visible flame. |
| 10-499 | Slow moving surface fires with relatively low flames. |
| 500-1999 | Moderately fast spreading fires with low and high flames. Isolated torching may occur if ladder fuels present. |
| 2000-3999 | Fast spreading , high intensity surface fires or intermittent crown fires with short range spotting. |
| 4000-9999 | Very fast spreading intermittent crown fires with flames extending above the canopy and short to medium range spotting. |
| 10,000-29,999 | Continuous crown fires with extremely fast spread rates. Fire whirls, towering convection column and medium to long range spotting possible. |
| > 30,000 | Continuous crown fires with extremely fast spread rates and long range spotting. Conflagration or blow-up type behavior possible. |

**Table 1. General fire behavior characteristics based on head fire intensity (adapted from Alexander and DeGroot 1998, Alexander and Lanoville 1989, Stocks and Hartley 1995, Hirsch 1996).**

System (Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). The FWI System provides a uniform method for assessing fire danger in Canada. It uses daily noon (local standard time) observations of temperature, relative humidity (RH), wind speed, and precipitation in the previous 24 hours to calculate three fuel moisture codes (Fine Fuel Moisture Code – FFMC; Duff Moisture Code – DMC; Drought Code – DC) and three general fire behavior indexes (Initial Spread Index –ISI; Buildup Index – BUI; Fire Weather Index – FWI). These components provide numerical ratings of relative fire behavior potential in a standard fuel type (e.g., mature pine) on level terrain. A compilation of 10 years (1989-98) of daily weather data from 8 stations located in or near the study area was obtained for the analysis. This period was the longest continuous record of weather data available for all 8 stations. Analysis was limited to the months of August and September (the most active portion of the fire season). Moreover, 15 days had inadequate information resulting in a weather database of 595 days.

The FBP System uses the FFMC, BUI, wind speed and wind direction, as well as fuel type and topographic information to calculate 15 quantitative fire behavior characteristics, including HFI. The FBP System has a total of 16 fuel types that represent most of the major fuel complexes found in Canada. Due to the empirical nature of the FBP System, it was necessary to classify the wide range of vegetation types in the study area into the most representative FBP System fuel type (Figure 2). This was completed using an Alberta Land and Forest Service program that converts the Alberta Vegetation Inventory (AVI) data into the most appropriate fuel types based on key stand structure and composition characteristics (Tymstra and Ellehoj 1994). Topographic data (i.e. slope, aspect, and elevation) was obtained from a digital elevation model. Spatial fuel and topography coverages had a 25 m resolution but the analysis was conducted at 100 m resolution to reduce computation time.

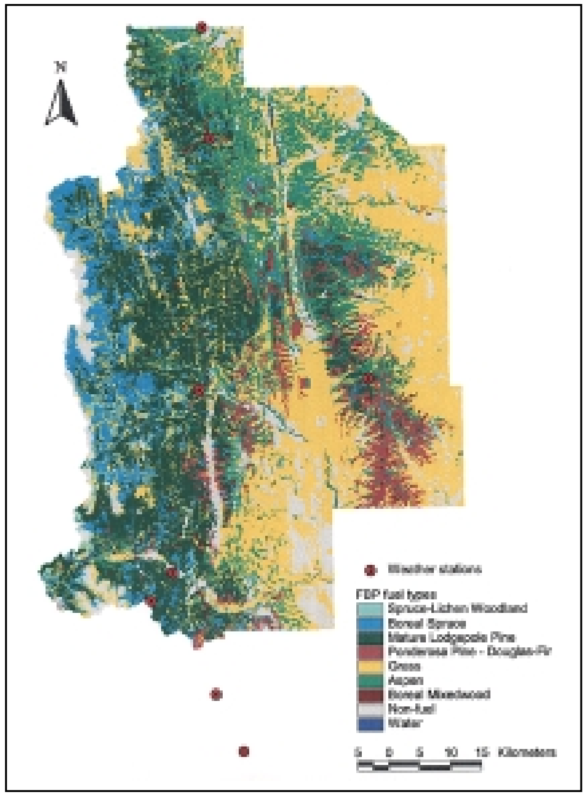


**Figure 2. FBP System fuel types and weather stations used in the study area.**

The ArcView GIS-based Spatial Fire Management System (sFMS) (Lee et al. 1997) was used to calculate the HFI values for every pixel in the study area. This system interpolates fire weather and fire danger data from the 8 stations over the landscape using an inverse distance weighted function (Flannigan and Wotton 1989); however, no attempt was made to adjust the weather data according to elevation or aspect.

Percentiles of HFI were used to assess the occurrence or frequency of different types of fire behavior in this area. For example, an 80th percentile HFI value of 7500 kW/m indicates that 80% of the time the HFI was at or below 7500 kW/m (and conversely, 20% of the time it was at or above this value). Percentile maps allow for a quick visual assessment of landscape-level fire behavior potential and by using a series of percentile maps (e.g., 50th, 60th, 70th, 80th, 90th, 95th), those areas with the highest fire behavior potential can be readily identified (Tymstra 1998).

### Calculation Methods

Two methods were used to calculate the spatial HFI percentile values for this area. The methods are similar in that both use the same raw input data and are computed using sFMS but they differ in how they derive the HFI percentiles (Figure 3). The daily method uses the daily FFMC, BUI, wind speed and wind direction values to produce an HFI grid for each of the 595 days in the study period. The HFI values for each cell are then ranked and sorted so the desired percentiles can be readily obtained. This method is rigorous but computationally demanding and time consuming when a large number of cells must be analyzed.

The climatological method begins with the calculation of the percentile values for the FFMC, BUI, and wind speed, as well as the dominant wind direction for each weather station for the study period. To obtain a particular percentile map, the fire weather/danger values for that percentile are entered into sFMS and a single HFI map is produced. This method only approximates the daily method but vastly decreases the amount of time required to produce a fire behavior potential map.

### Statistical Comparison

Descriptive and comparative statistics were used to compare the two calculation methods for selected percentiles. A map showing the arithmetic difference between the two methods (i.e. climatological HFI percentile value minus daily HFI percentile value) at the 80th percentile was also produced. The HFI values were also categorized into general fire behavior classes and the percentage of correct (i.e. identical) classifications was obtained using equation 1:

$$\text{Percent correct} = \left(\sum_{i=1}^{c} e_{ii}\right) \Big/ N * 100 \qquad (1)$$

where the sum of “correctly classified” diagonal elements of the contingency matrix ($e_{ii}$) for all classes (c) is divided by the total number of pixels (N). A high percent correct value implies that most pixels are found to be in the same fire intensity class.

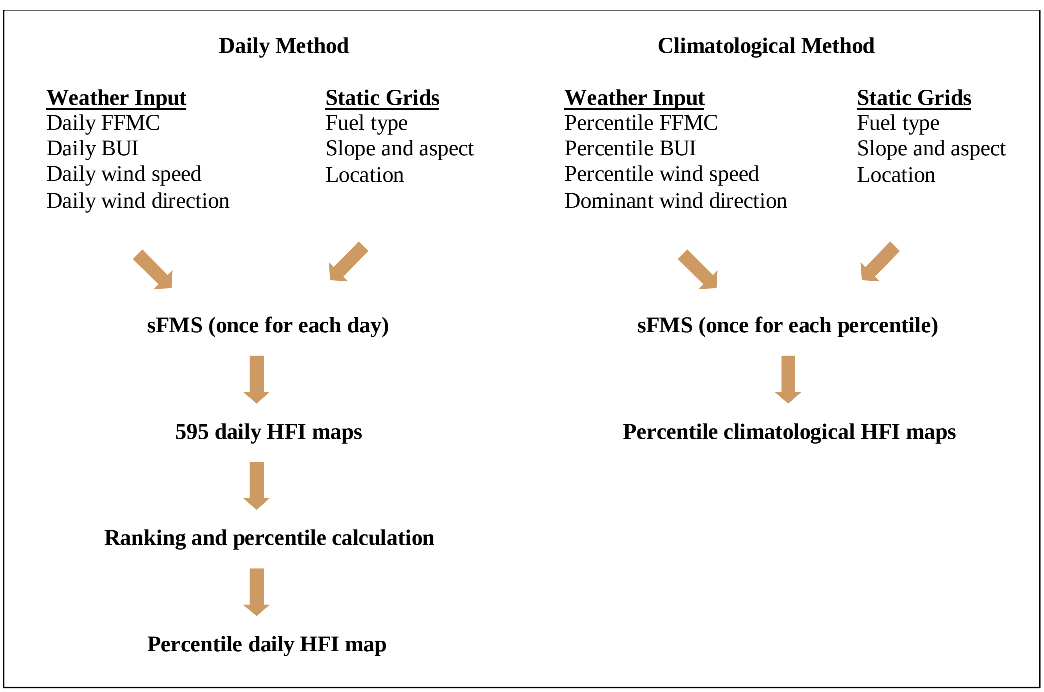


**Figure 3. Calculation procedures for the daily and climatological methods.**

## RESULTS AND DISCUSSION

Table 2 provides a summary of the proportion of the study area within each fire intensity class at selected percentile levels for the two calculation methods. It shows that at the 50th and 60th percentiles, most of the study area had a low or moderate fire intensity classification. This suggests that a majority of the time severe fire behavior will not occur during August and September in this area. As the percentile level increases, larger portions of the study area have higher fire intensities. At the 95th daily percentile 37% of the area has an HFI above 10,000 kW/m, indicating that on average there are 5% of the days in August and September when over one-third of the study area could support high intensity crown fires which would be difficult to control.

The percentile maps (Figure 4) provide valuable insights about the spatial distribution of fire behavior potential. For example, at the 90th percentile almost all of the high and extreme HFI values appear in the western half of the study area whereas the low and moderate HFI values are found in the eastern and central areas which are dominated by grasslands and aspen forests. In addition, locations with the highest fire behavior potential are readily identified because they continue to have extreme HFI values as the percentile level decreases. These areas are situated mostly in the western portion of the study area where steep slopes and the boreal spruce fuel types are common. Identification of these high fire behavior potential areas is critical from a fire and forest management perspective because they will be candidates for proactive fuels treatments that could reduce the fire spread and crowning potential.

| Percentile | Method | Area (ha) in each head fire intensity (kW/m) class | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0-9 | 10-499 | 500-1999 | 2000 - 3999 | 4000 - 9999 | 10,000 - 29,999 | greater than or equal to 30,000 |
| 50th | Daily | 130,100 | 206,800 | 62,300 | 23,700 | 13,600 | 900 | 0 |
| | Climatological | 151,800 | 185,100 | 66,300 | 16,300 | 14,800 | 3100 | 0 |
| 60th | Daily | 61,800 | 127,100 | 191,900 | 15,000 | 33,000 | 8500 | 0 |
| | Climatological | 61,000 | 126,000 | 181,000 | 25,800 | 30,600 | 12,500 | 600 |
| 70th | Daily | 33,900 | 39,600 | 271,100 | 37,500 | 31,000 | 23,500 | 900 |
| | Climatological | 27,500 | 50,800 | 239,300 | 47,900 | 39,300 | 28,900 | 3800 |
| 80th | Daily | 15,300 | 51,800 | 188,900 | 85,500 | 41,400 | 48,300 | 6200 |
| | Climatological | 17,800 | 40,600 | 178,400 | 70,600 | 60,100 | 57,600 | 12,300 |
| 90th | Daily | 700 | 53,900 | 126,400 | 71,900 | 76,800 | 83,200 | 24,500 |
| | Climatological | 10,600 | 29,500 | 102,200 | 100,300 | 56,200 | 91,600 | 47,000 |
| 95th | Daily | 0 | 33,100 | 73,600 | 109,300 | 57,500 | 98,900 | 65,000 |
| | Climatological | 2000 | 22,900 | 54,500 | 99,900 | 77,600 | 60,200 | 120,000 |

**Table 2. Areas observed in each head fire intensity class at selected percentiles for the daily and climatological methods.**

The comparison of the two methods for calculating fire behavior potential showed that in general the HFI values derived by the climatological method were higher than those produced by the daily method (compare Figures 4c and 5a). The main reason for this is that the climatological method uses independently calculated percentiles for the FFMC, BUI, and wind speed. This procedure results in an overestimation of the fire weather/danger conditions because the joint probability of these values all occurring at the same time is lower than their occurrence independently. For example, at the Blairmore weather station, the 90th percentiles for the FFMC, BUI, and wind speed were 92.6, 111.9, and 25 km/h respectively. These values were simultaneously equaled or exceeded (joint probability) on just one of the 595 days analyzed.

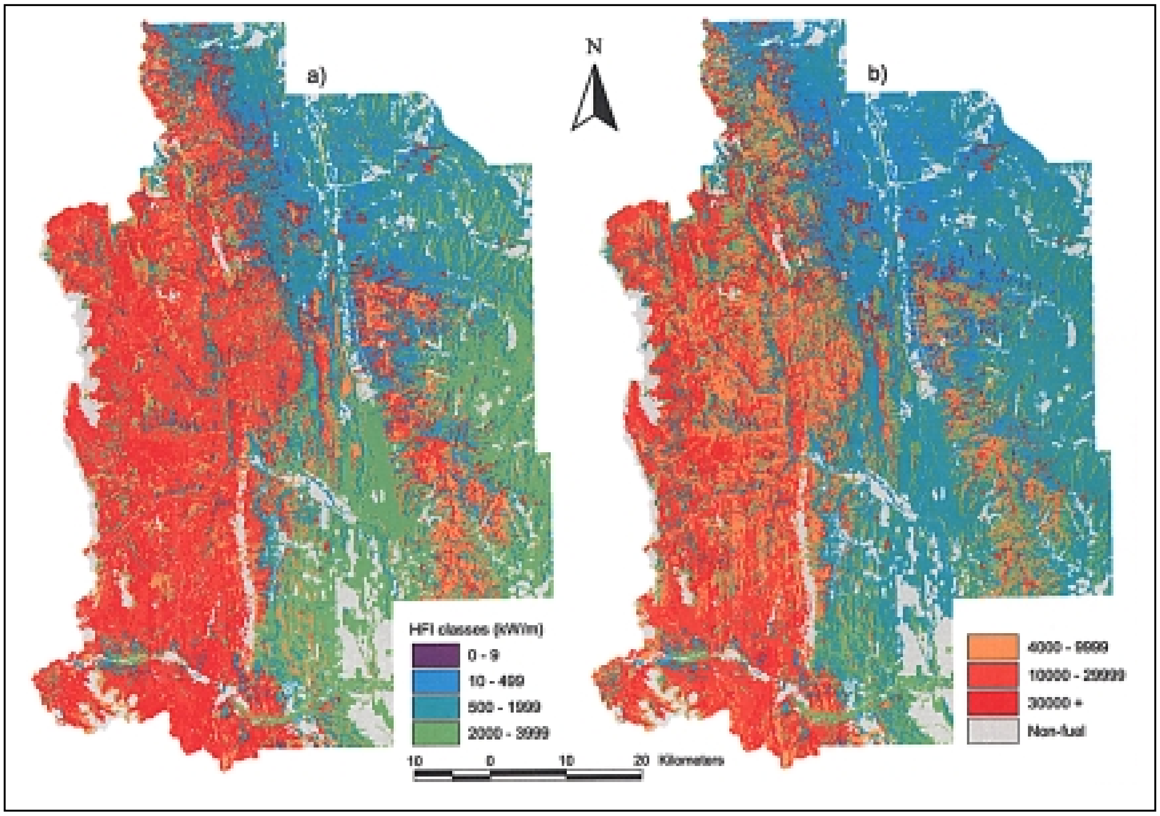


**Figure 4. Head fire intensity calculated for the daily method at a) 95th percentile and b) 90 the percentile.**

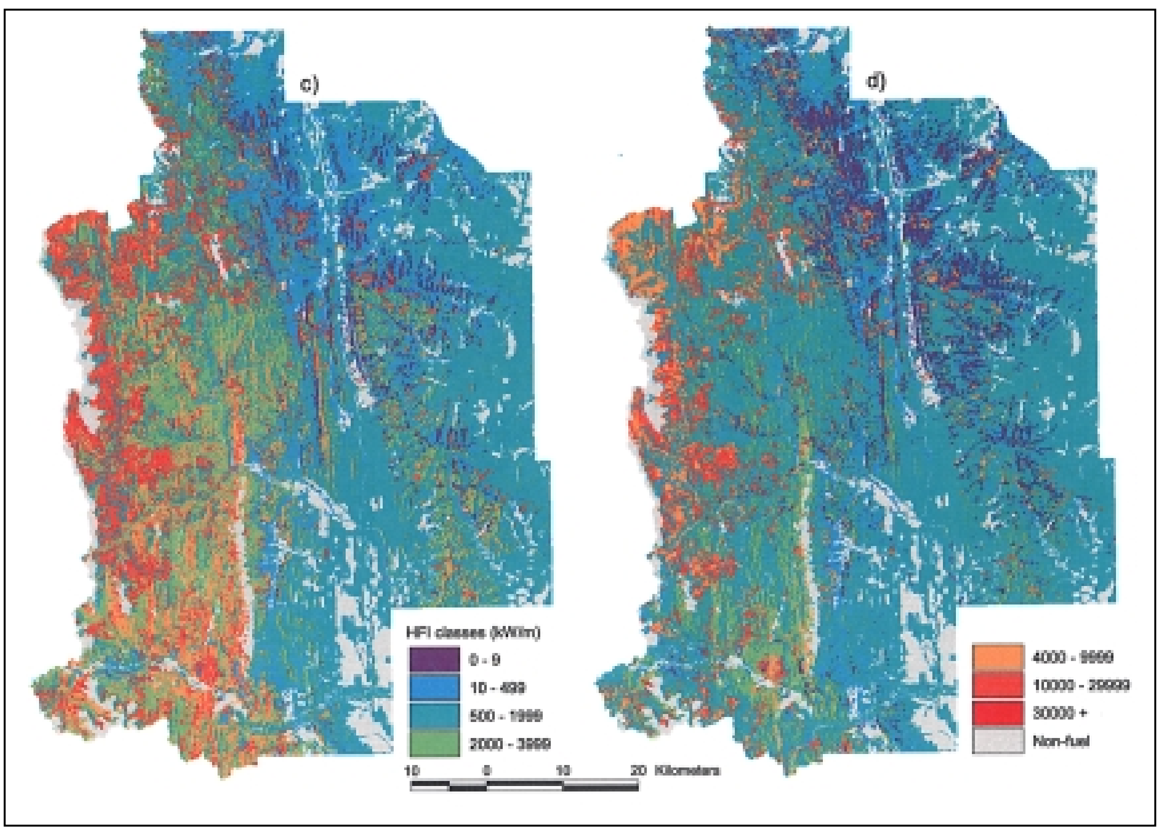


**Figure 4. (continued) c) 80th percentile and d) 70th percentile.**

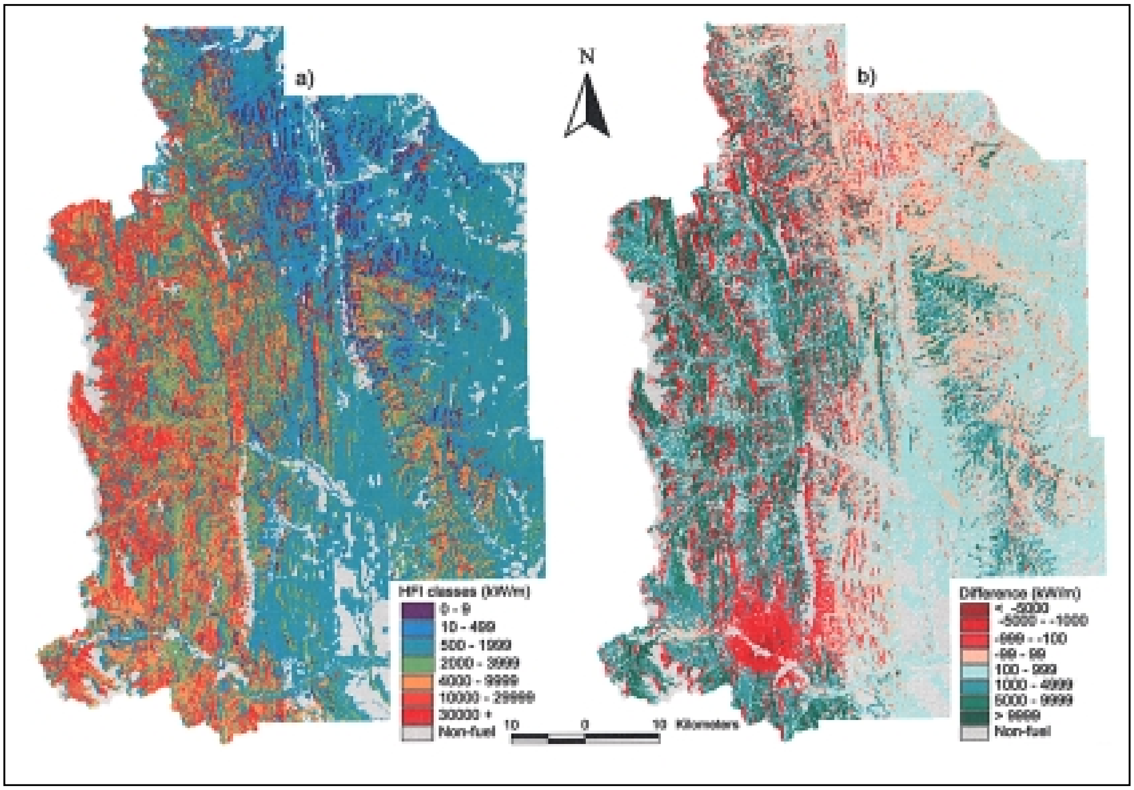


**Figure 5. a) Head fire intensity calculated for the climatological method at the 80th percentile and b) difference in head fire intensity between the methods at 80th percentile (climatological -daily method).**

Figure 5b shows that although overestimation is most common, there are also cells in which the climatological method underestimates the daily method. Further analysis revealed that these underestimates were occurring on east facing slopes while extreme overestimates were on west facing slopes. These effects are attributed to the interactive effect of slope and wind on rate of spread and to the use of a dominant wind direction in the climatological method rather than one that varies each day.

As indicated in Table 3, the percent correct decreases considerably as the percentile level increases. In fact, only 53% of pixels were found in the same HFI class at the 95$^{th}$ percentile. This trend is also a result of the use of independently calculated estimates of the fire weather/danger parameters in the climatological method. On the other hand, the linear correlation between the two methods remains relatively high at all percentile levels.

Figure 6 provides the distribution of difference values for a subset of the 80$^{th}$ percentile HFI values ranging from 2000 kW/m to 10,000 kW/m. This distribution is positively skewed (i.e. it has a long right side tail) and shows that the climatological method produces values that are frequently and sometimes much higher (e.g., greater than 10,000 kW/m) than those provided by the daily method. Conversely, underestimation occurs less often and is mostly within 2000 kW/m of the daily method. Based on this result, it is recommended that the daily method be used whenever possible; the climatological method can be an alternative (i.e. especially if joint probabilities are calculated) but its limitations must be fully acknowledged.

| Percentile | % Correct | Correlation |
|---|---|---|
| 50th | 83.8 | 0.95 |
| 60th | 76.3 | 0.95 |
| 70th | 79.2 | 0.95 |
| 80th | 71.0 | 0.95 |
| 90th | 59.4 | 0.93 |
| 95th | 53.5 | 0.89 |

**Table 3. Percent correct and correlation relating the daily and climatological head fire intensity percentile methods.**

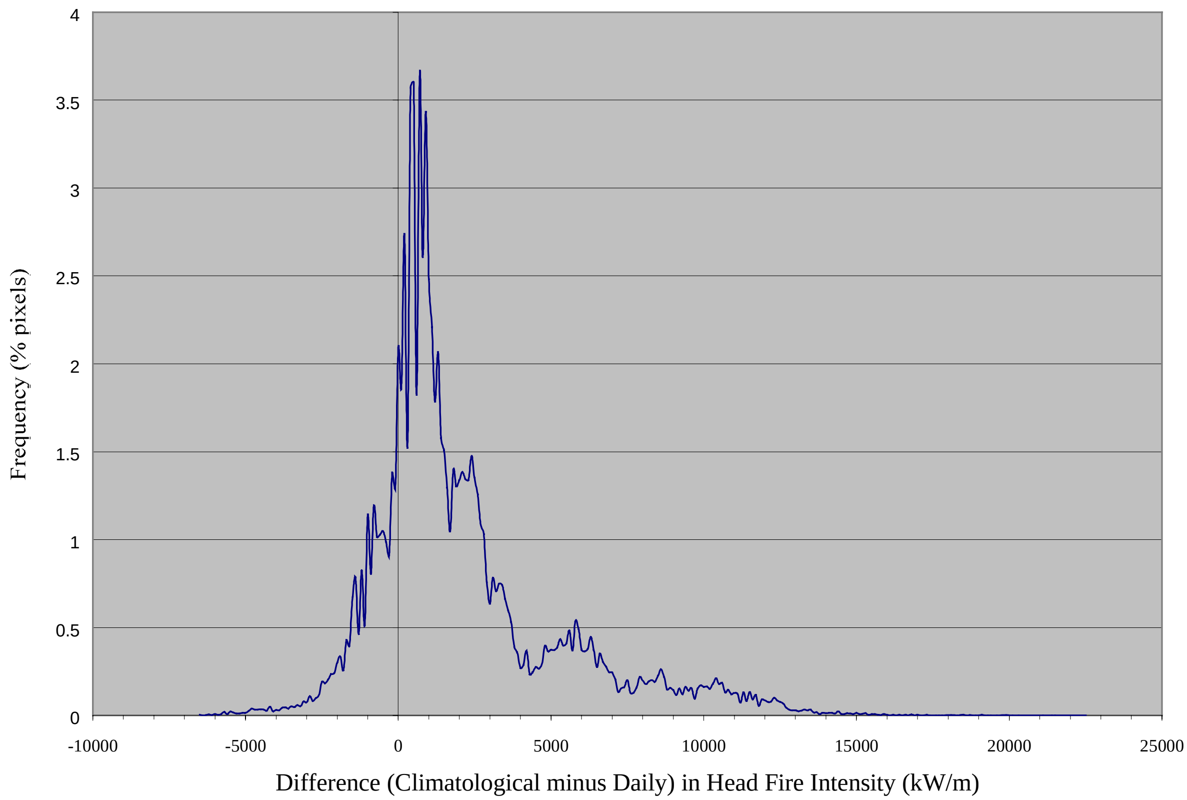


**Figure 6. Distribution of 80th percentile head fire intensity values showing the difference between the climatological and daily methods for daily values between 2000 and 10,000 kW/m values.**

## CONCLUSIONS AND FURTHER RESEARCH

Spatial and quantitative assessments of the fire behavior potential over large landscapes can be obtained when spatial fuels, weather, and topographic data are used in conjunction with the FBP System and sFMS to compute HFI values. This information can help to identify areas of high or extreme fire behavior potential for use in fire suppression, fuels management and other types of fire and forest management activities.

Of the two calculation methods used to obtain spatial HFI percentile maps in this study, the daily method provides the most representative assessment of fire behavior potential but it is more computationally demanding. The climatological method is much faster and requires less computing power but tends to overestimate the fire behavior potential, especially at the higher percentile levels. Selection of the most appropriate technique will depend on computational capability, availability of time, and desired accuracy of the results.

Both methods could benefit from better input data and spatial modeling. This includes the use of procedures that would interpolate data from multiple weather stations by elevation and aspect. As well, the use of radar precipitation estimates could provide more accurate spatial FFMC values (Flannigan et al. 1998b). Finally, validation and refinement of the FBP System fuel type classification from the Alberta Vegetation Inventory would also enhance the analysis.

The type of quantitative analyses used in this study could be combined with values-at-risk data and probabilistic models of fire occurrence and suppression capability to quantitatively assess wildfire threat. The techniques presented here could also be used with projections of vegetation succession (e.g., Taylor et al. 1998) and fire weather (Flannigan et al. 1998a) to gain insights into future fire regimes resulting from changing climatic condition and landscape disturbances. Finally, it is necessary to conduct the same type of comparative analysis in a significantly different fire environment (e.g., a boreal forest area) to determine if similar results will occur.

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## REFERENCES


Alexander, M. E. and DeGroot, W. J. (1988). Fire behavior in jack pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. Poster with text. Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.

Alexander, M. E. and Lanoville, R. A. (1989). Predicting fire behaviour in the black spruce-lichen woodland: the Porter Lake Project. Poster with text. Forestry Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta and Government of the Northwest Territories, Department of Renewable Resources, Fort Smith, NWT.

Byram, G. M. (1959). Combustion of forest fuels. In: *Forest Fires: Control and Use*. K. P. Davis (ed.). New York: McGraw-Hill, pp. 61-89.

Chatto, K. (1998). Development of wildfire threat analysis model for south-eastern Australia. In: *III International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology,* Nov. 16-20. 1998. Luso, Portugal. Vol. II, pp. 2243-2254.

Flannigan, M. D. and Wotton, B. M. (1989). A study of interpolation methods for forest fire danger rating in Canada. *Canadian Journal of Forest Research* 18(8): 1059-1066.

Flannigan, M. D., Bergeron, Y., Engelmark, O. and Wotton, B.M. (1998a). Future wildfire in circumboreal forests in relation to global warming. *J.Veg.Sci*. 9: 469-476.

Flannigan, M. D., Wotton, B. M. and Ziga, S. (1998b). A study of the interpolation of fire danger using radar precipitation estimates. *International Journal of Wildland Fire* 8(4): 217-225.

Forestry Canada Fire Danger Group. (1992). Development and structure of the Canadian Forest Fire Behavior Prediction System. Inf. Rep. ST-X-3, Forestry Canada, Ottawa, Ontario.

Forestry Canada and Alberta Forest Service. (1992). Ecoregions of Alberta. Poster with text. Canada-Alberta Partnership Agreement in Forestry, Forestry Canada, Northern Forestry Centre, Edmonton, Alberta, and Alberta Environmental Protection, Forest Service, Edmonton, Alberta.

Hawkes, B., Beck, J. and Sahle, W. (1996). A wildfire threat rating system for the McGregor model forest. In: *13th Conference on Fire Forest Meteoolog.,* Lorne, Australia (In Press).

Hirsch, K. (1996). Canadian Forest Fire Behavior Prediction (FBP) System : user's guide. Special Report 7, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta.

Hirsch, K. G., Corey, P. N. and Martell, D. L. (1998). Using expert judgment to model initial attack fire crew effectiveness. Forest Science 44(4): 539-549.

Lee B. S., Todd, J. B. and Suddaby, R. M. (1997). A Spatial Fire Management System. In: *IX Silvotecna Conference Proceedings*, Nov 17-18. 1997. Concepcion, Chile.

Longley, R. W. (1972). The climate of the prairie provinces. Climatological Studies Number 13, Environment Canada, Atmospheric Environment Service, Toronto, Ontario.

Rowe, J. S. (1972). Forest Regions of Canada. Catalogue No. F047-1300, Canadian Forest Service, Department of Fisheries and the Environment, Ottawa, Canada.

Sneeuwjagt, R. (1998). Applications of wildfire threat analysis in south-western forest of Western Australia. In: *III International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology,* Nov. 16-20. 1998. Luso, Portugal. Vol. II, pp. 2155-2176.

Stocks, B. J. and Hartley, G. R. (1995). Fire behavior in three jack pine fuel complexes. Poster with text. Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, Ontario.

Taylor, S. W., Baxter, G. J. and Hawkes, B. C. (1998). Modeling the effects of forest succession on fire behavior potential in southeastern British Columbia. In: *III International Conference on Forest Fire Research and 14th Conference on Fire and Forest Meteorology,* Nov. 16-20. 1998. Luso, Portugal. Vol. II, pp. 2059-2071.

Tymstra, C. and Ellehoj, E. A. (1994). Fire behavior prediction and fuel type mapping using the Alberta Vegetation Inventory. In: *Proceedings GIS'94 Symposium,* Feb. 1994. Vancouver, B. C., pp. 887-893.

Tymstra, C. (1998). Fire Management Planning: The Southern Rockies Landscape Planning Pilot Project. Alberta Environmental Protection, Land and Forest Service, Forest Protection Division, Edmonton, Alberta.

Van Wagner, C. E. (1987). Development and structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report 35, Canadian Forest Service, Ottawa, Ontario.